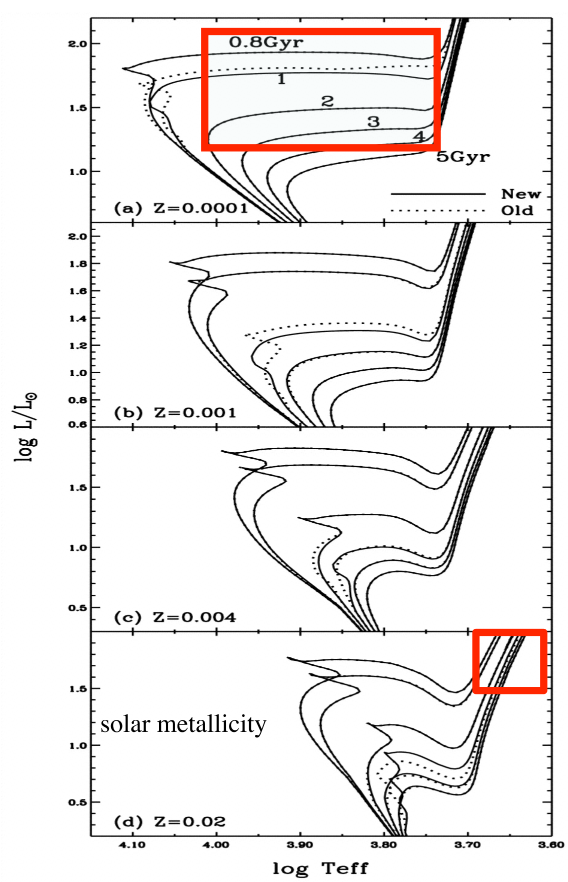
This Time

- Age of a SSP
- SSP spectra as a function of time
- Initial Mass Function (IMF)
- Composite spectra of galaxies

Theoretical Isochrones

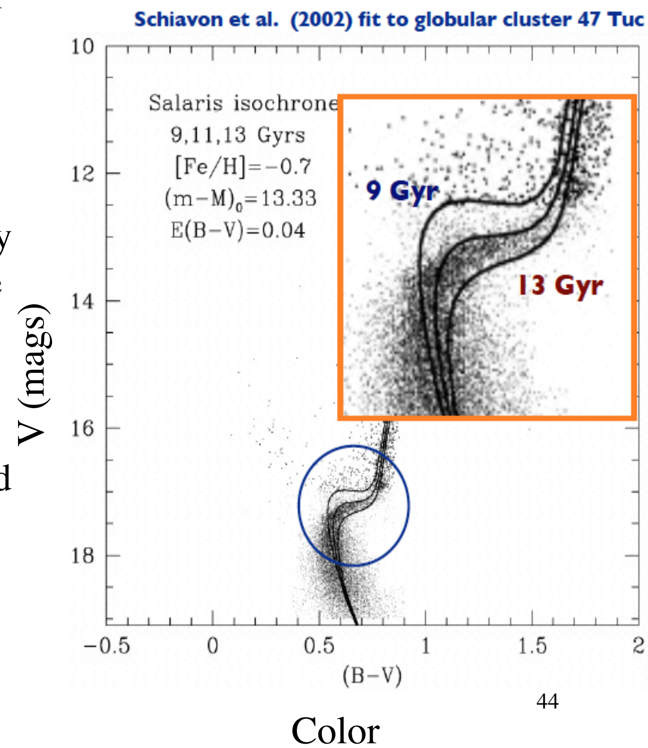
- These lines are the positions of stars from a SSP as a function of the age of the system - in the temperature/ luminosity plane **if** no new stars are born
- The shape depends on the metallicity of the stars (Demarque et al 2004)

- One can determine the '*age*' of the system by fitting an isochrone (if one has data for individual stars) or by calculating some average property (color/spectrum) averaging over the isochrone - <u>degeneracy problems with age and metallicity are obvious</u> -
- notice stars 'pile up' on the red giant branch (dominate luminosity of old systems)



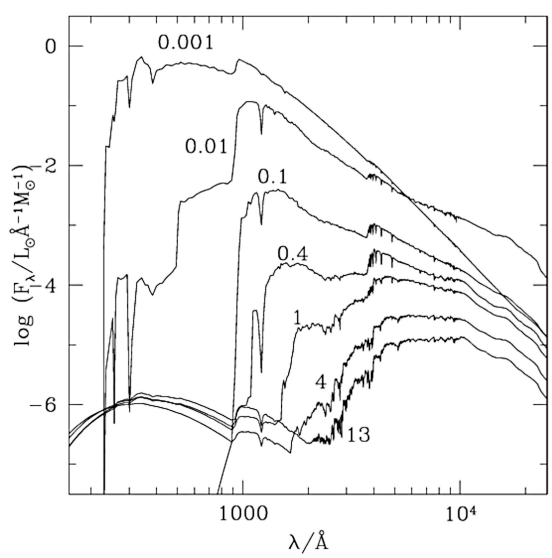
Age Dating a SSP

- Globular clusters can be well approximated by a SSP and are frequently chemically homogenous
- With precision photometry ages can be well estimated by measuring the location of the 'turn-off'- e.g. when the star leaves the main sequence.
  - (because stars at same distance, can use observed brightness, V, instead of absolute luminosity)



Galaxy Spectra

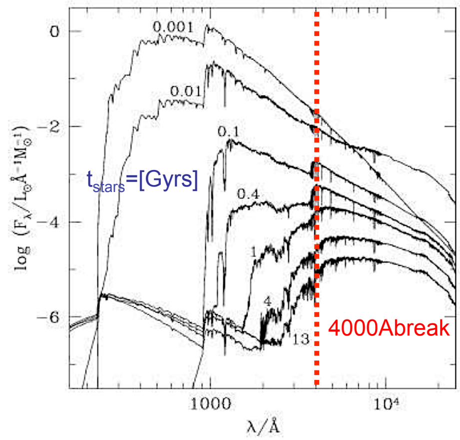
- Of course the galaxy spectrum is the sum of the stars, weighted by their luminosity.
- The spectra changes radically with the age of the system (MBW fig 10.5) and weakly with chemical composition
- After a ~fewx10^9 yrs stars on the red giant branch dominate the ~1μ flux; stars on the red giant branch have a narrow range of parameters for a large range in mass; good estimator of mass in stars (discussion in sec 10.3.3 MBW)

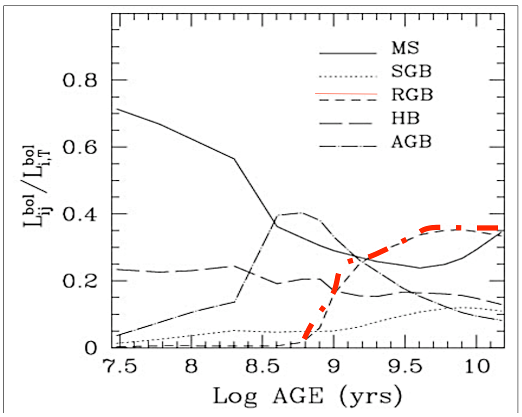


Theoretical spectrum of a SSP with a Saltpeter IMF and solar metallicity at a variety of ages 0.001-13 Gyrs

Luminosity and Colors Changes of a SSP

- As SSP ages the relative luminosity due to different parts of the H-R diagram changes
  - young systems MS dominated by massive stars
  - Older systems(>2Gyrs)-dominated by red giant branch
  - If star formation is a continuous process which stars produce most of the luminosity and where most of the stellar mass lies can be quite different





Spectral energy distribution UV-IR of a SSP as it ages

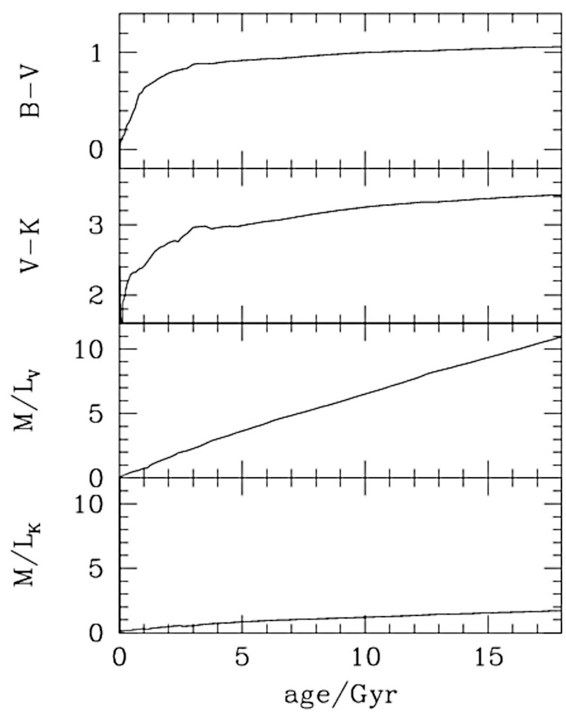
Notice the enormous changes in the UV and blue

A slow fading in the IR

Age Dating A SSP

- If one just has colors then the H-R diagram is not so useful; the colors of a SSP can be calculated as a function of age (for a given metallicity) (See MBW pg 473)
- Notice the weak change in color vs age after ~3Gyrs, but the strong change in M/L_V and weak change in M/L_K

- ***why? please explain why these plots look like they do.***
  - ***Hints: K band is in the near IR, V band is in the optical***



- The physical origin of the form of the IMF is not well understood
- Use the stellar mass-luminosity relation and present day stellar *luminosity* function together with a model of how the star formation rate varies with time.
- Simplest description: Salpeter- pure power law $\Phi(m)=N(M)\sim M^{-\alpha}\,dM$ for $M>M_{\odot}$ (Salpeter 1953)- total mass diverges $\alpha\sim 2.35$ (eq 2.5 S&G)
- Near the sun one can observe several 'open' star clusters (Scalo 1986)
  - one finds that the slope changes below ~ $1M_{\odot}$ (e.g. flattens)
- There is a severe technical issue- it is only in the MW, MW globular clusters and the Magellanic clouds that one can measure individual stars over a large mass range. All other estimates of the IMF depend on integrated properties and thus are more model dependent
  - there is also a fundamental problem; how to handle binary stars !

IMF- **MBW 9.6**
S&G 2.1.2

INITIAL Mass Function

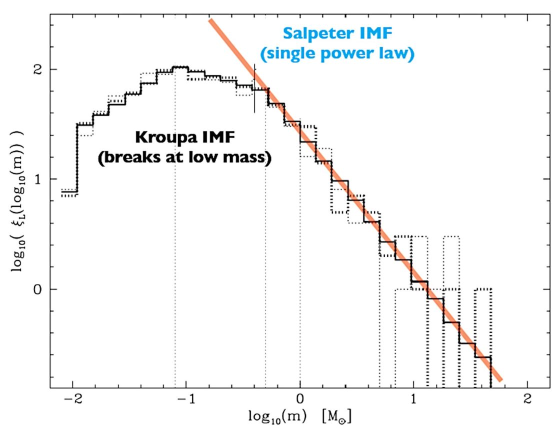
mass range $[M_{\odot}]$	% by number	% by mass
0.01 - 0.08	37.2	4.1
0.08 - 0.5	47.8	26.6
0.5 - 1	8.9	16.1
1 - 8	5.7	32.4
8 - 120	0.40	20.8
$<m>$	0.38 $M_{\odot}$	

70 Pavel Kroupa: AIfA, Uni

Review Chabrier- Publications of the Astronomical Society of the Pacific, 115:763–795

Initial Mass Function-IMF S&G sec 2.12

- The distribution of stellar masses at t=0 (birth)
- The origin of the form of the IMF is not well understood
- There are several forms proposed
  - Saltpeter- $\Phi(m)=N(M)\sim M^{-2.35}dM$ for $M>M_{\odot}$ (Salpeter 1953)
    - much of integrated stellar mass near $1M_{\odot}$
  - Kroupa/Scalo/Chabrier IMFs- flatten at low masses
- At present it is controversial if the IMF is universal or a function of age, metallicity, density etc



Luminosity function
$\Phi(x)$ = [number of stars with $M_V - 1/2 < x < M_V + ½$]/]volume Vmax(MV) over which these could be seen]

Salpeter Mass Function

- The Initial Mass Function for stars in the Solar neighborhood was determined by E.Salpeter in 1955.
- $\Phi(m)=\Phi(0)M^{-2.35}$: $\Phi(0)$ is a constant which sets the local stellar density
- Using the definition of the IMF, the number of stars that form with masses between M and M + ΔM is: $\Phi(m)\Delta M$
- To determine the total number of stars formed with masses between M_1 and M_2 integrate the IMF between these limits:
- $N=\int\Phi(m)dM=\Phi(0)\int M^{-2.35}dM =[\Phi(0)/1.35][M_1^{-1.35}-M_2^{-1.35}]$

and total mass is $\int M*\Phi(m)dM=[\Phi(0)/0.35][M_1^{-0.35}-M_2^{-0.35}]$

- most of the stars (by number) are low mass stars
- most of the mass in stars resides in low mass stars
- following a burst of star formation, most of the luminosity comes from high mass stars

Steps to the IMF-adapted from Djorgovski/Scalo-http://www.astro.caltech.edu/~george/ay20/Ay20-Lec17x.pdf

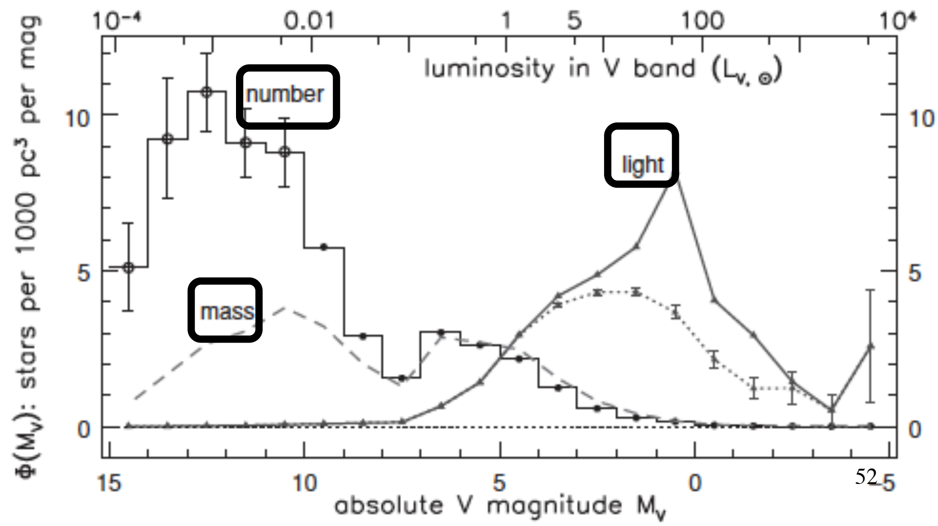
Determining the IMF is difficult
• Start with observed star counts
– Understand your selection effects, completeness
– Get the distances
– Correct for extinction
– Correct for unresolved binaries
Take the data and determine the luminosity function (LF),
Then apply: correction for main sequence lifetimes, and evolved stars no longer visible

• Get the Present-Day Luminosity Function (PDLF)
– Assume a mass-luminosity relation
which is a function of metallicity, bandpass, …
– Theoretical models tested by observations
and the mass-luminosity (m-L) relation using stellar structure theory

• Convert to Present-Day Mass Function (PDMF)
– Use the evolutionary tracks from the same theoretical models
– Iterate over a star formation history
• Get the Initial Mass Function (IMF)

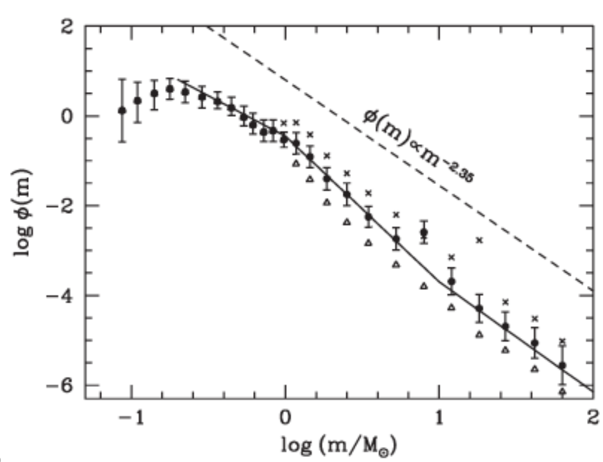
Number, Luminosity and Mass Functions

- S&G Fig 2.3 The histogram shows the luminosity function (MV) for nearby stars: solid dots
- Lines with triangles show $L_V\Phi(M_V)$, light from stars in each magnitude bin; the dotted curve is for main-sequence stars alone, the solid curve for the total. The dashed curve gives $M_{MS}\Phi(M_V)$, the mass in main-sequence stars. Units are L or M per 10 pc cube.



IMF-see MBW pg 440

- General form $\int m\Phi(m)dm=1M_\odot$
- integrated over the upper and lower mass range of stars ; meaning $\Phi(m)dm$ is the number of stars born with mass m+/- δm for every $M_\odot$ of newly formed stars
- Stars $M<0.08M_\odot$ nuclear fusion not take place and $M>\sim120M_\odot$ are unstable.



5. The IMF from Scalo (1986) for field stars in the solar neighborhood. For $m > 1 M_\odot$ the thı
ıts represent results assuming different ratios of the current star-formation rate to the average o
ıe of the solar neighborhood. The solid lines show the broken power law (9.41), while the dash

- Kroupa IMF $\Phi(M)=dN/dM = A\ M^{-1.3}$ $(0.1 \le M_\odot \le 0.5)$

  $= 0.5\ A\ M^{-2.3}$ $(0.5 \le M_\odot \le 100)$

Kroupa IMF has 1.6x less total mass than the Saltpeter IMF for the same normalization but ~ same amount of light

$\langle M\rangle=0.6M_\odot$

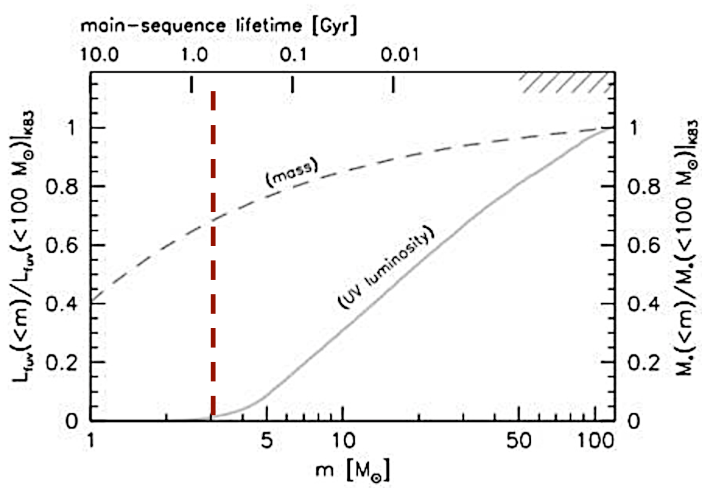
Effects of IMF

- an IMF with a slope of = 2.4 for stars above $1M_\odot$ produces 10^8 stars with $M > 8M_\odot$ for a galaxy of total stellar mass 10^{11} $M_\odot$ while a Kroupa (2001) IMF gives 10^9 such stars – a factor of 10 times more.
- This change in the number of massive stars is very important for the chemical enrichment of the galaxy since only stars of $M>8M_\odot$ produce type II SN.
- For example, the mass of O^{16} released by massive stars for the slope 2.4 case, produces a 7 times lower than solar oxygen abundance and Kroupa.

- The slope of the IMF is, critical for converting the observed light to stellar mass - this is extremely important for determining the baryonic mass in spiral and elliptical galaxies and is a major source of uncertainty.

Focus on The UV

- The UV emission of a star forming galaxy driven by high-mass stars ($M > 10M_\odot$).
- The short main-sequence lifetimes of these stars indicates that the UV luminosity is a diagnostic of the star formation rate.
- BUT the UV emission from a star forming galaxy is produced by stars with a range of masses, and thus main-sequence lifetimes.



Solid line- how much UV luminosity comes from stars more massive than m- dotted line how much of the total stellar mass comes from these objects

Wilkins et al 2012

Stellar Populations I & II- Baade 1942 (pg 56 MBW) S&G sec 6.3

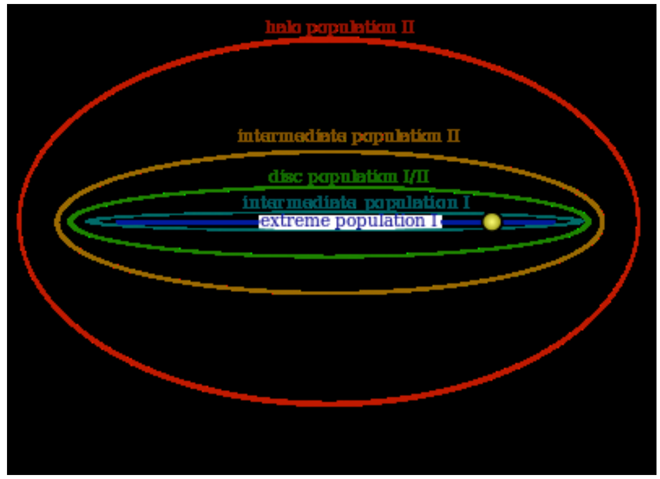
In spiral galaxies there are 2 'types' of stellar populations

Population I
- Young
- Metal rich
- in disks
- Rotationally supported

Population II-' red'
- Old
- Metal poor- non-solar abundances
- Found in Globular clusters, Spiral bulges
- dispersion supported

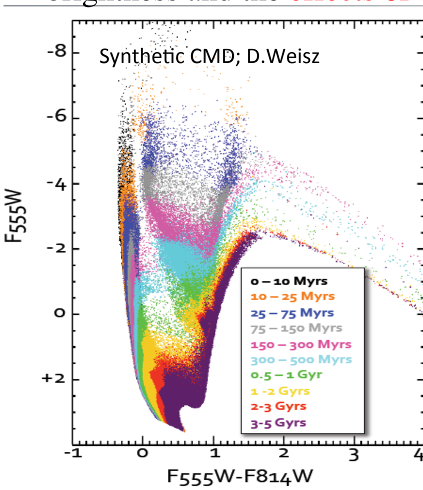
- But **not** in Ellipticals- these stars are old- but frequently metal rich, thus different than spiral Pop II

theoretically there is also Pop III- the first stars



Schematic picture of stellar pop's in Milky Way

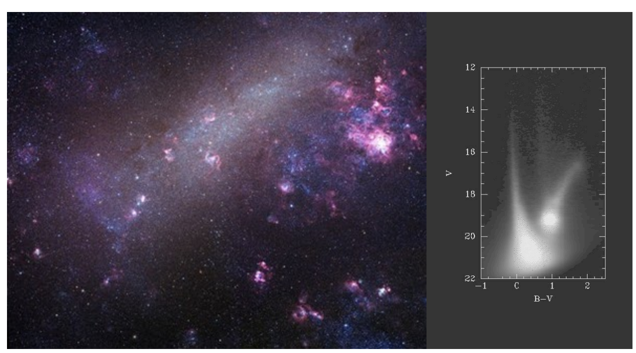
- Different parts of a galaxy have different ages and metallicity
- Only for the MW, SMC, LMC (and with Hubble a few nearby galaxies) can one construct a H-R diagram which shows this
- For distant galaxies we have to deal with integrated spectra colors and brightness and the effects of dust.



Galaxies are NOT SSPs

H.Rix2010

LMC:Zaritsky&Harris 2004-2009

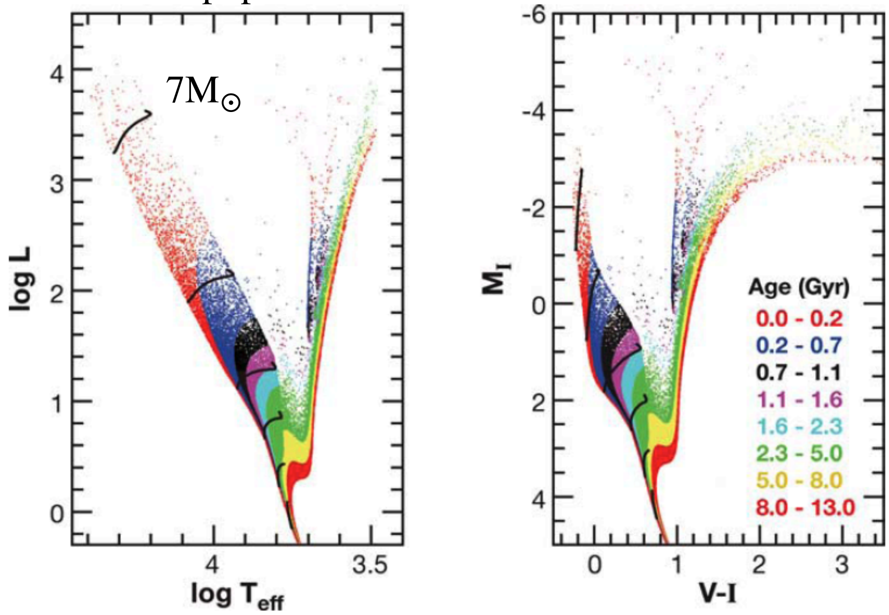


LMC:Zaritsky&Harris2004-2009

Galaxy $=\Sigma_{(time)}$SFR(t) xSSP(t;Y; Z; IMF)

Y the Helium abundance and Z the abundance of heavier elements (metallicity)

What does a population with continuous Star formation look like??



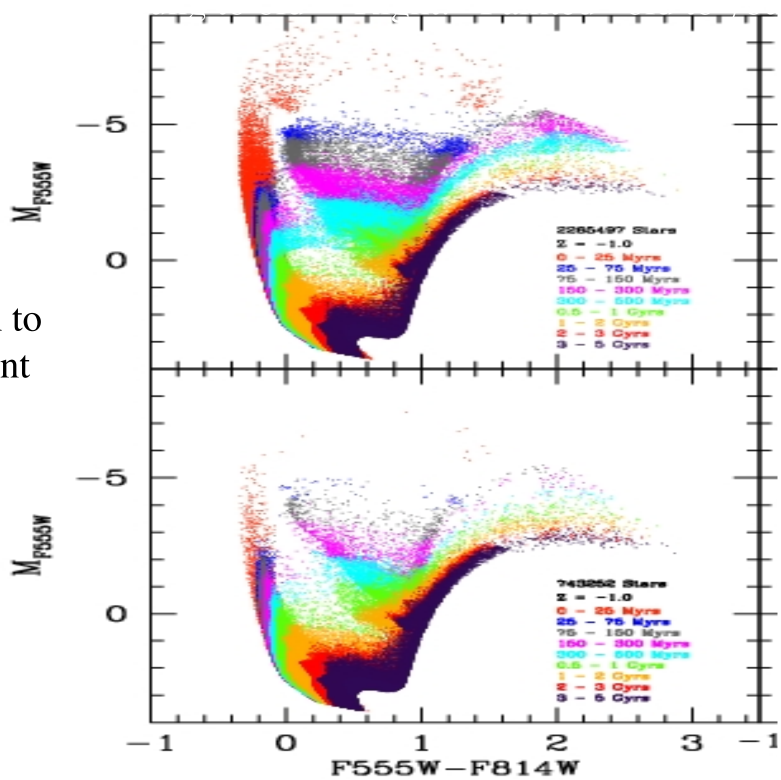
- **Theoretical space (left), observational space (right)**
- **Constant SFR** from 13Gyr ago to the present time, Z =0.0198, IMF slope-2.3
- **stellar evolutionary tracks for stars of masses 7, 3, 1.9, 1.5, 1.2, and1$M_\odot$**

What does this look like?
SFR * IMF * flux for individual stars (before it's integrated over all stars…)
(Eric Bell)

Top panels:
Increasing SFR to emphasize recent star form

Bottom panels:
constant SFR

CMDs created by D. Weisz using Dolphin's codes

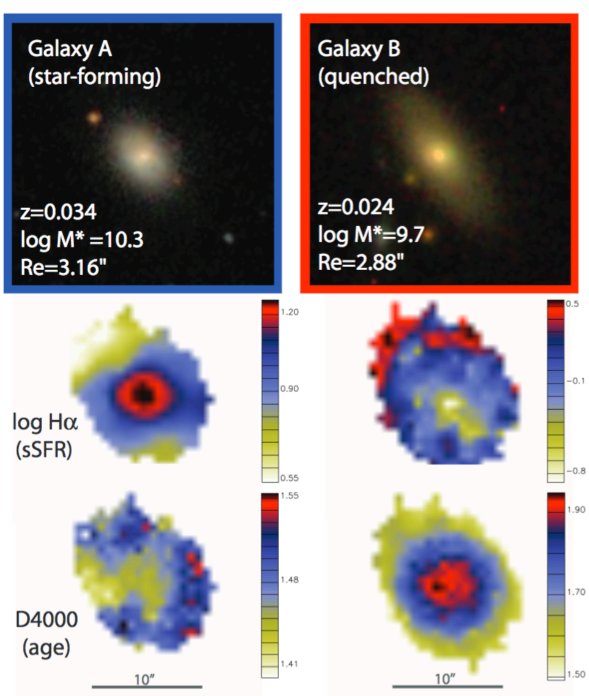


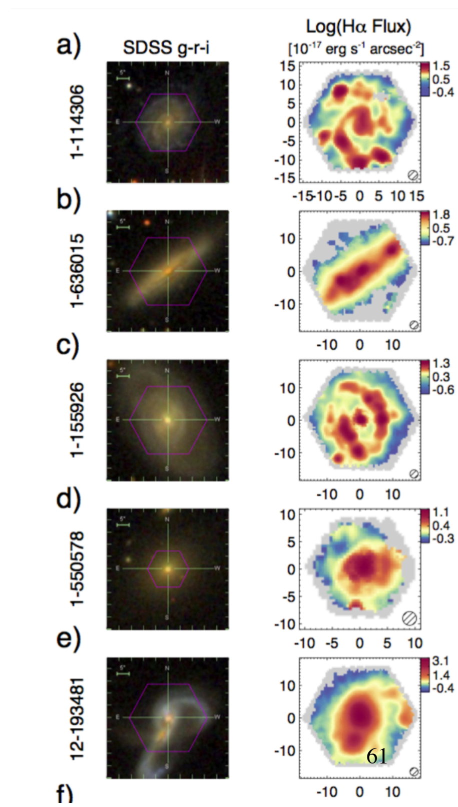
Color Magnitude Diagrams

- Need to measure individual stars- only possible in local group
- <u>But Very powerful</u>
  - If get to main sequence turn off for old stars
    - Star formation history
      - Resolution good for recent star formation, worse for ancient times
  - If you don't get to main sequence turn off (more distant objects)
    - Some SFH information remains but tricky to do well because it's all post-main sequence based

- However for the vast majority of galaxies just have integrated spectra/ color images
  - New data with spatially resolved spectra (IFUs)- e.g MANGA (more later) sub-divide galaxy into ~100 places (~1 kpc) for 10,000 (!!) galaxies

MANGA Data

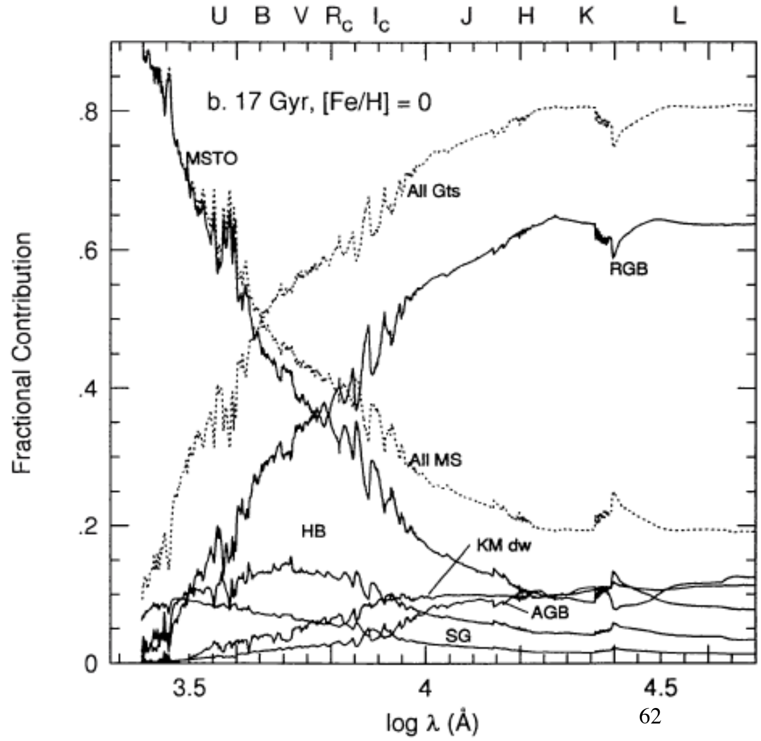




Origin of Light

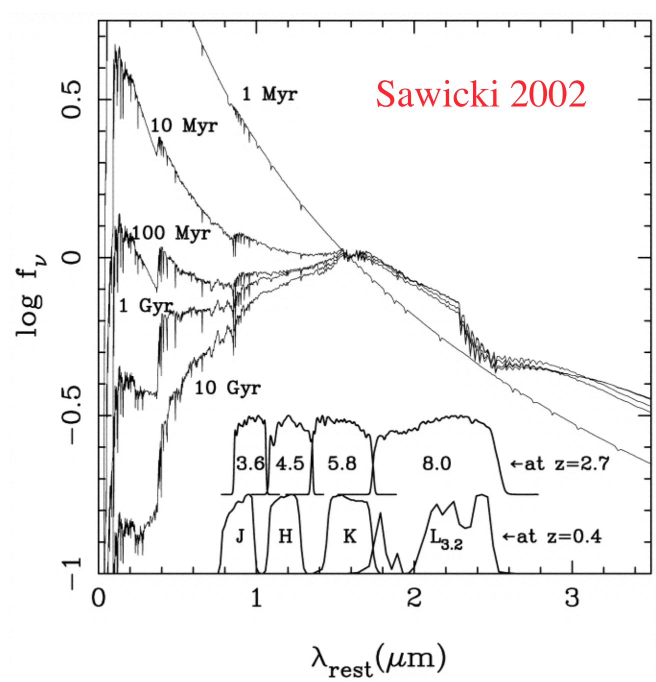
In a SSP which stars produce the observed light as a function of wavelength

Graph is a snap show at an age of 17 Gyrs !) (Worthey 1994)



How Much Light at Which Wavelengths

- As a SSP system ages the spectrum changes strongly at short wavelengths but remains ~ constant at long wavelengths
  - K band (2.2μ) is thus a good proxy for stellar mass at all times

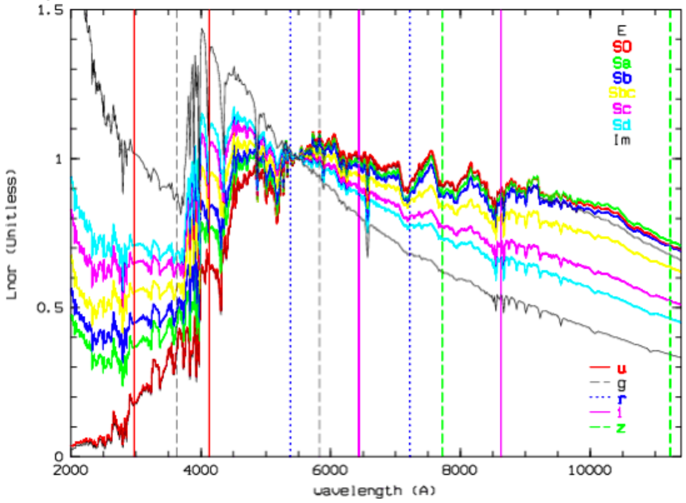


General Trends for SSPs

- Populations fade as they age
- – ionizing flux is only produced for t<20 Myrs
- – Fading by 10^5 at 3000Å from 10 Myrs to 10Gyrs
  - – UV flux is only produced for 0.2Gyrs
- X 100 at 5000Å from 0.1Gyrs to 10Gyrs
- X 6 at 1.5μ from 1Gyr to 10Gyrs
- – populations 'redden' as they age

the ratio of the current SFR over the average past SFR is very important in determining the spectrum of a galaxy.

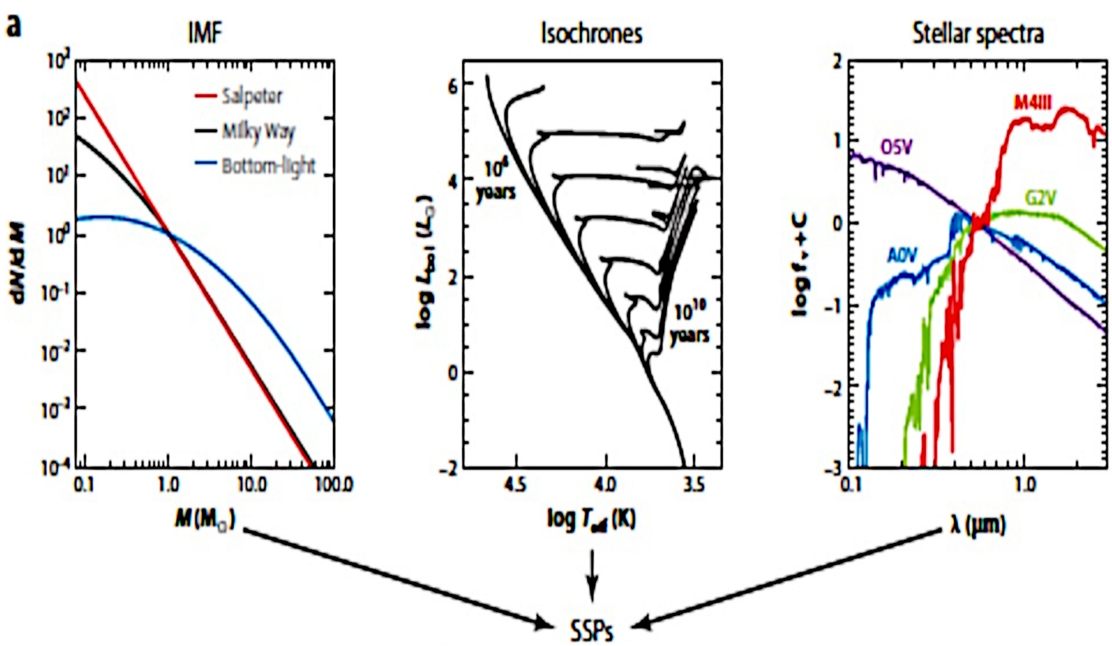
Higher 'metallicity' and dust also 'redden'



Theoretical models of galaxy composite spectra

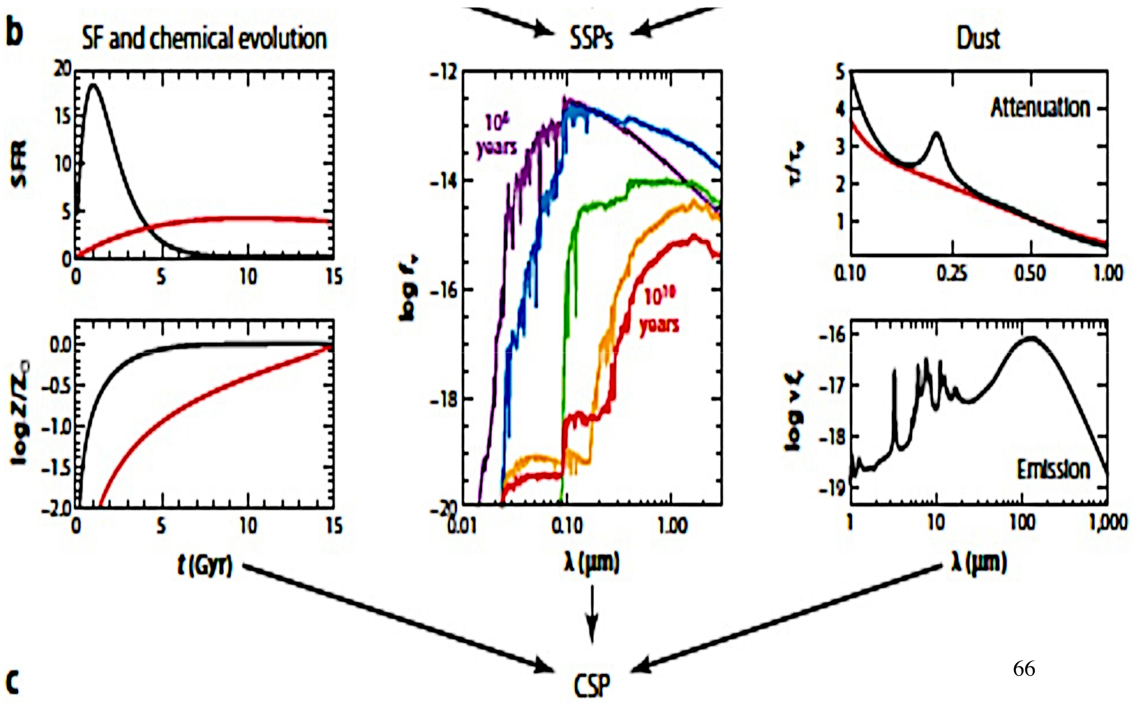
What is the Process –MWB sec 1.3 Conroy 2013

Taking stellar models and data and constructing a galaxy spectrum



What is the Process –MWB

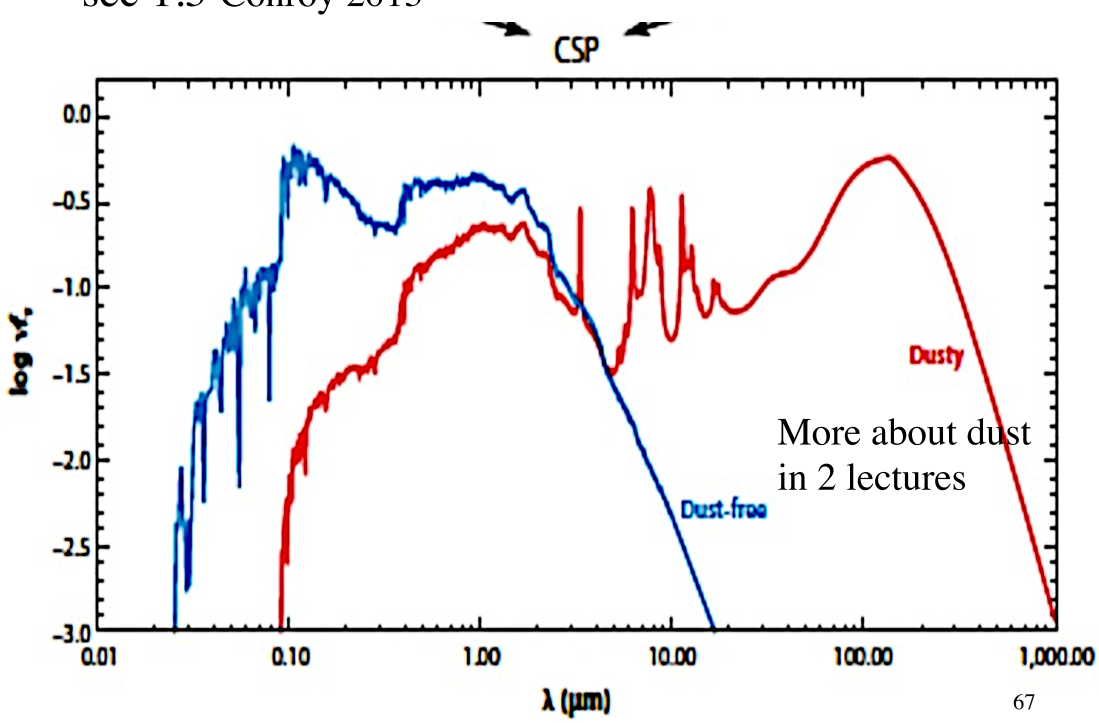
sec 1.3 Conroy 2013



66

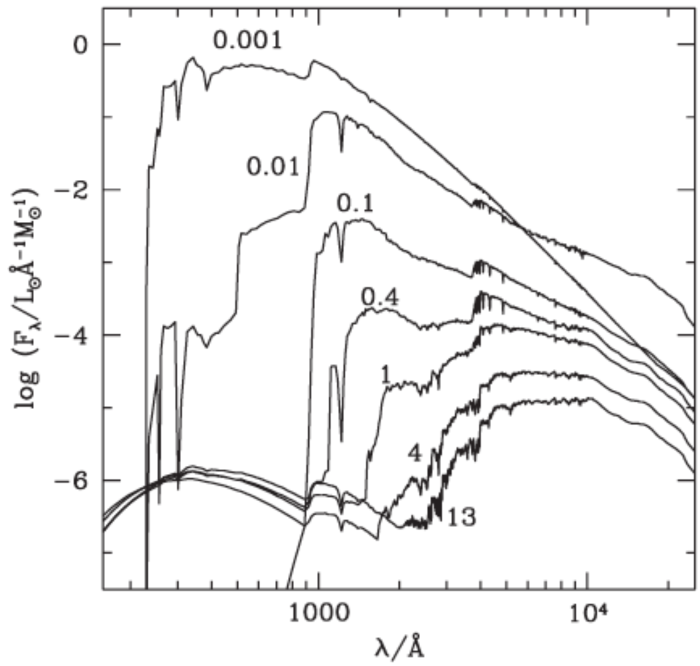
What is the Process –MWB

sec 1.3 Conroy 2013



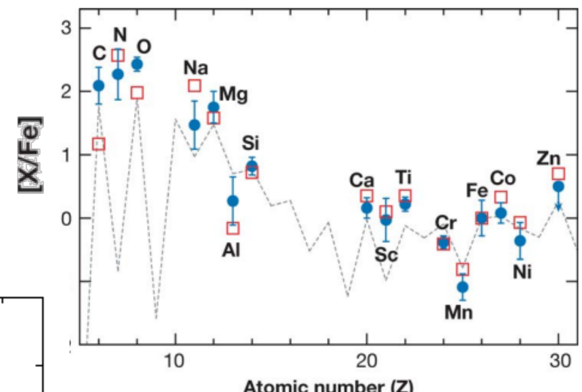
67

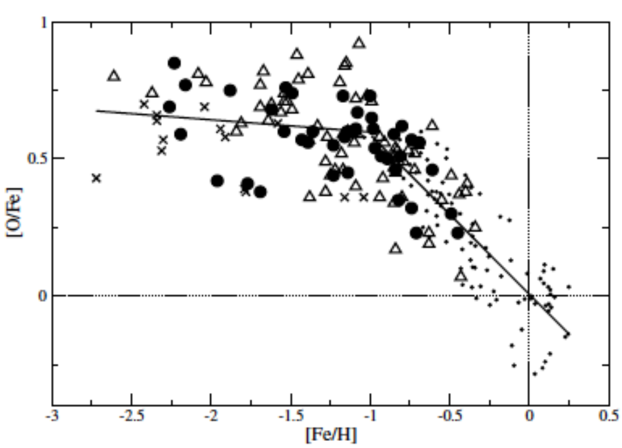
Spectra for a SSP as a function of Age (in Gyrs)



Abundance Pattern of OLD Metal Poor Halo Stars (pg 177 in S+G)

- A strong clue to the formation of the **<u>first</u>** stars - lots more C, N,O relative to Fe.
- *We will have a more general lecture on chemical evolution later*



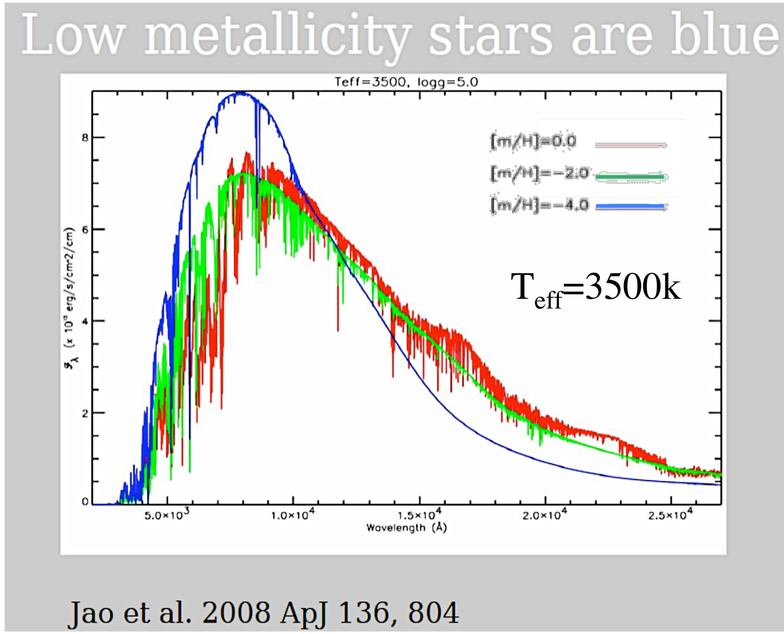


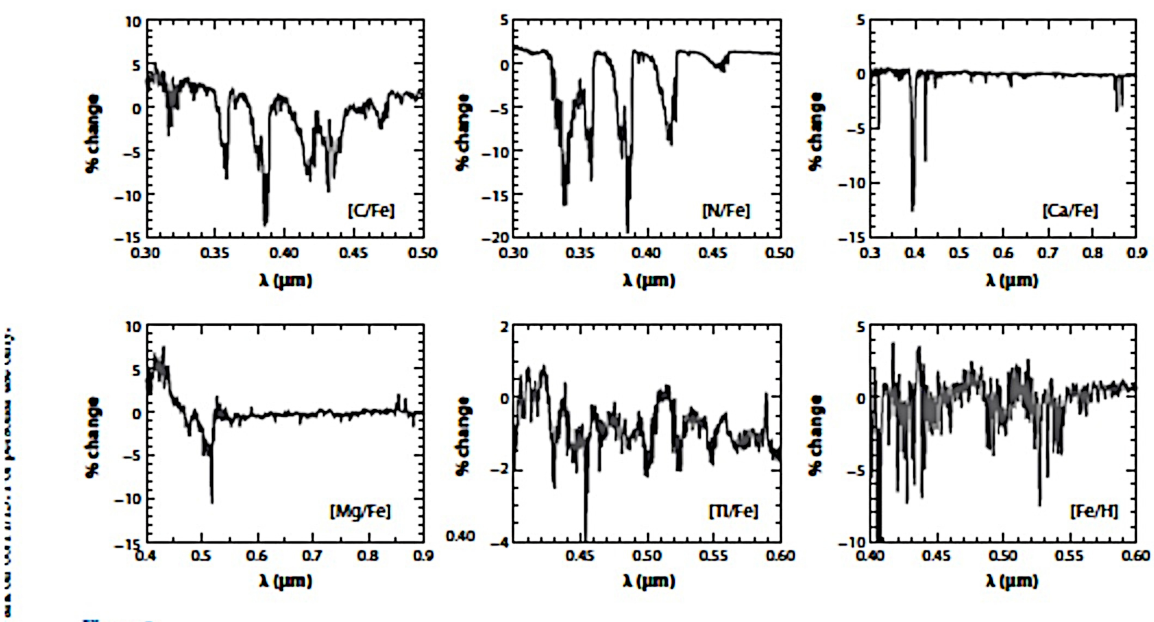
[X/Fe] is the logarithmic ratio of element X to Fe with respect to the sun's abundance pattern

- At a given mass/ temperature the colors of metal poor stars are 'bluer'- due to less line blanketing* in their atmospheres

*The decrease in intensity of a star's spectrum due to many closely spaced, unresolved absorption lines.

Effects of Metallicity





- Effects of change in abundance for different elements on a 13Gyr old stellar population- effects at the few percent level

Spectra of Galaxies

- Mathematically the luminosity of a galaxy at a given frequency, ν, is
  $L_\nu(\text{galaxy})=\int dt' \int dZ'(dM/dt(t,Z) x L_\nu^{(SSP)}(t-t', Z', \phi)$
  - where Z is metallicity at a time t, dM/dt is the formation rate of stars of metallicity Z at time t and $L_\nu^{(SSP)}$ is the luminosity at this frequency of a SSP of metallicity Z, age t and IMF ϕ
  - $L_\nu^{(SSP)} = \int \phi\,(M')L_\nu^{(star)}\,(t, Z)\,dM'$ over the range of masses (e.g. M_{min}-M_{max})
- there are theoretical libraries which calculate for different ages, IMFs and metallicities
- These are constructed using a combination of theoretical stellar evolution models, observations of stars of known age and metallicity and theoretical models of stellar atmospheres where no good observations exist.

  - see the A. Benson review article eqs 114,115

72

- The Flux at one wavelength=

$$\iiint f_\lambda(M,Z,t)\ \psi(t,Z)\ n(M)\ dM\ dZ\ dt$$

- n(M) - the stellar IMF
- $\psi(t,Z)$ - the star formation history
- $f\lambda(M,Z,t)$ - stellar library, complicated…
- Critical assumptions
  - Universally-applicable stellar IMF which we *know* and how the star formation rate evolves

How to Use this Information

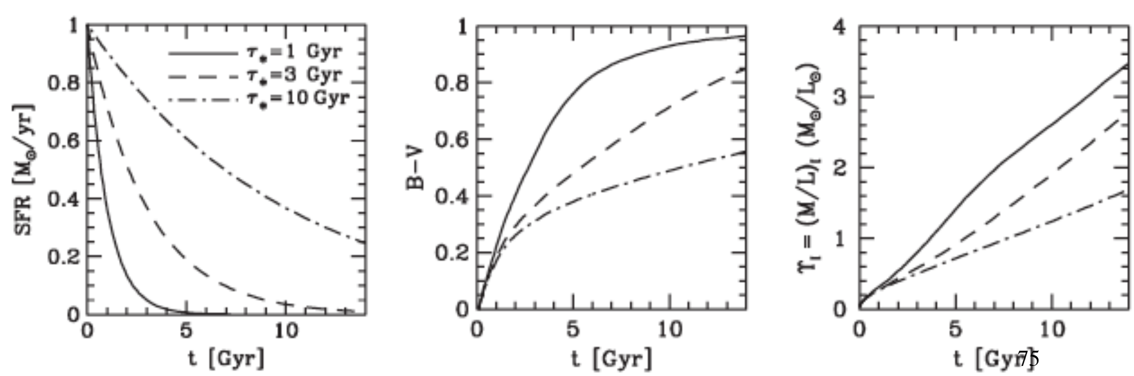
- ‘Integrated’ Stellar Populations

Crucial since only 10-100 Galaxies have resolved stars

- What can we say about stellar mass, metallicity, star formation history age– for low z galaxies can resolve 'parts' of the galaxy, for most distant objects 'whole' galaxy
- Data
  - images
  - colors, or ‘many colors’, i.e the ‘spectral energy distribution’ (SED) (R=5 spectrum)
  - Spectra (R=2000) (integrated or spatially resolved spectra or long slit)
- It is not possible to invert the data to derive the desired parameters.
- Process:
  - assume stellar formation history and IMF- generate isochrones
  - use stellar library to calculate spectra/colors
  - iterate and see if it converges

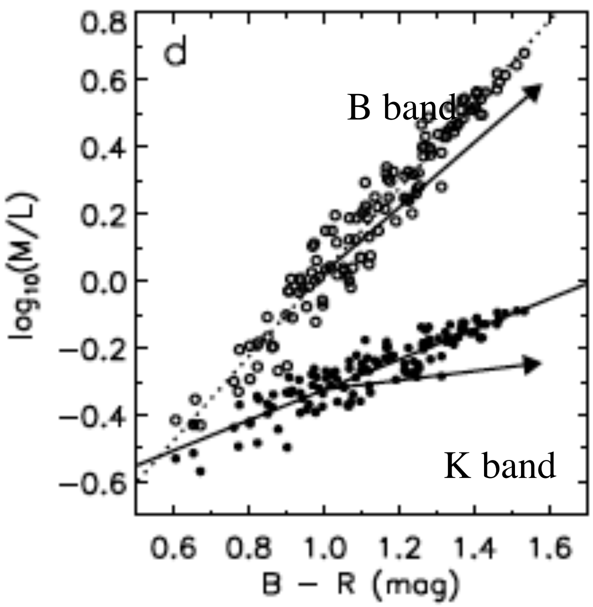
Effect of Star Formation History on Colors and Luminosity of a SSP (fig 10.9 of MBW)

- Left panel 3- different star formation histories
  - solid 1 Gyr e-folding time
  - dash 3 Gyr
  - -dash-dot .. 10 Gyr
- Middle panel B-V colors
- Right Panel mass to light ratios



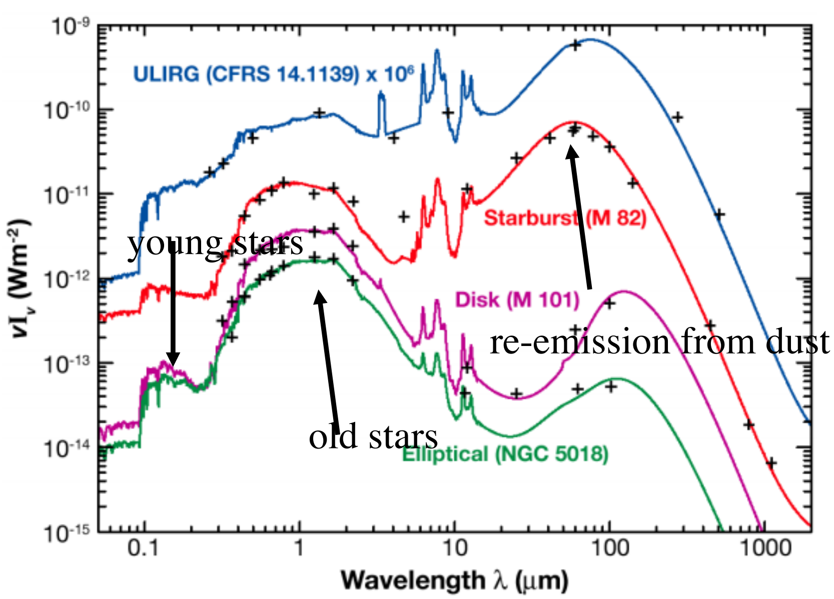
M/L(Mass to Light) Indicators

- Some colors are very sensitive to M/L
- Strong correlation between stellar M/L and the optical colors
- For a composite population one has to make a lot of assumptions: SF vs time law, chemical evolution model, SSP model, etc etc- color is basically ratio of how much SF now to how much in the past
- Such techniques can be applied to large samples -



Put it All Together Into A Galaxy

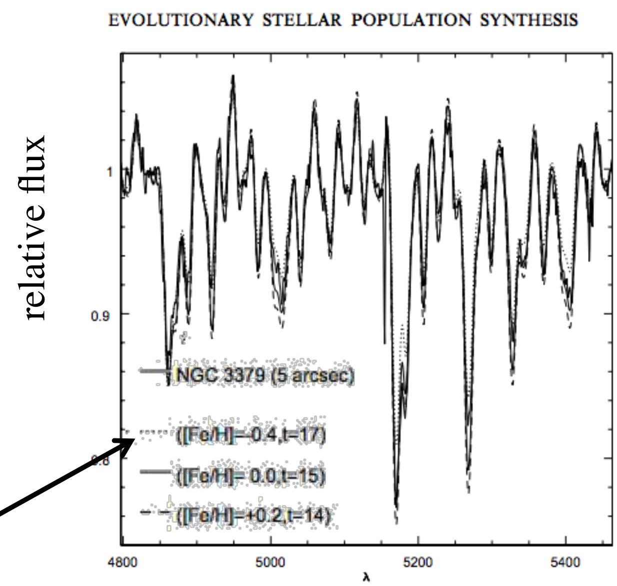
- Even some ellipticals have dust



http://hubblesite.org/newscenter

Summary Spectra of Galaxies see MWB sec 10.3.2-10.3.6

- Almost all the energy radiated by 'normal' (not AGN) galaxies is due to stars (either direct or reprocessed)
- However the stellar spectra is a triple integral over
  - IMF
  - star formation history
  - stellar library
- furthermore the observed spectrum is often strongly effected by dust
- Also there is a <u>'age/metallicity' degeneracy</u>; for much of the optical band spectra young, metal-rich populations strongly resemble old, metal-poor populations



wavelength

Vazdekis 1999

Next Time

- GAS- physics of ... S+G 2.4+5.2
- MBW sec 10.3.7,10.3.8